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An Instrumentation System for the
Rapid Measurement of Run to
Detonation Distances

Tim Bussell and Chanphu Lam

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An Instrumentation System for the Rapid Measurement of Run to Detonation Distances

Tim Bussell and Chanphu Lam

**Weapons Systems Division
Aeronautical and Maritime Research Laboratory**

DSTO-TR-0129

ABSTRACT

An instrumentation system for the measurement of run to detonation distances in an explosive acceptor has been developed. The system comprises dedicated hardware elements for data acquisition and user friendly, graphical software for the analysis of the measured data. The system has been designed to allow results to be output in a graphical format with fast turnaround times between firings.

This report presents a detailed description of the hardware and software components of the instrumentation system and outlines the standard operating procedures in the application of the system to run to detonation measurements. Results from the measurement of run to detonation distances in steel covered, confined and unconfined Composition B which demonstrate the advantages of this system are presented and discussed.

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An Instrumentation System for the Rapid Measurement of Run to Detonation Distances

Executive Summary

The distance that a shock wave runs in an explosive prior to transitioning to a detonation is an important parameter in defining the behaviour of energetic materials to various stimuli. A range of experimental techniques including flash x-ray, optical or electronic probing can be used to measure this distance, although often, the techniques do not give rise to immediate results and some do not have general applicability due to experimental constraints such as highly fragmenting rounds. A computerised instrumentation system for the measurement of run to detonation distances in an explosive acceptor was developed and applied to experiments with confined and unconfined explosives. The system consists of several elements of hardware used to generate and record electric pulses within a reacting explosive acceptor, together with graphical analytical software for the analysis of the pulses. Software relating the predicted transit time of the initiating shock to the measured transit time of the shock front through the explosive, recorded by the electronic probes, calculates the run to detonation distance. The analysis takes place on site and results are achieved within a few minutes of firing the round.

Although initially designed for use with shaped charge jets, the system can be used in experiments in which the initiation stimulus is able to be described by a mathematical relationship. Various charge geometries can also be accommodated, with up to five different materials covering the explosive. This feature makes it possible to investigate a range of experimental scenarios including underwater or underground charges.

A description of the instrumentation system and numerical method for calculating the run distance is given in the report, together with operating details for the numerical software. Example results for unconfined and steel confined Composition B initiated by a shaped charge jet are presented which show good reproducibility of the measurements and demonstrate the effect of confinement for initiation by a shaped charge jet.

Authors

Tim Bussell

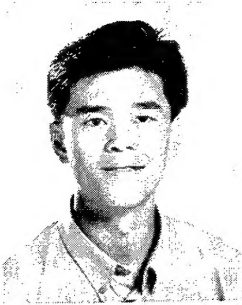
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Tim Bussell studied at the Royal Melbourne Institute of Technology, graduating BAppSc (with Distinction) in Applied Physics. He began work at AMRL in 1982 and has been involved in the development and application of various experimental methods to study explosive phenomena. He has had several years experience with flash x-ray systems and is currently developing manganin gauge techniques for application to high pressure measurements in explosives.

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Contents

| | |
|---|----|
| 1. INTRODUCTION | 1 |
| 2. SYSTEM OVERVIEW | 1 |
| 3. SYSTEM OPERATION | 3 |
| 3.1 Hardware Elements | 3 |
| 3.1.1 Probe event box and power supply | 3 |
| 3.1.2 Recording instrumentation | 6 |
| 3.2 Software Elements | 7 |
| 3.2.1 General development details | 7 |
| 3.2.2 Acquisition software | 9 |
| 3.2.3 Run to detonation calculation software | 9 |
| 4. RUN TO DETONATION MEASUREMENTS | 14 |
| 4.1 Use of the Run to Detonation Program | 14 |
| 5. RESULTS AND DISCUSSION | 21 |
| 6. CONCLUSIONS | 26 |
| 7. ACKNOWLEDGEMENTS | 26 |
| 8. REFERENCES | 26 |
| APPENDIX A: Description of the Acquisition Software | 28 |

1. Introduction

The distance that a shock wave runs in an explosive prior to transitioning to a detonation is an important parameter in defining the behaviour of energetic materials [1]. This measurement of the run to detonation distance is a useful approach for investigating the effects of parameters such as charge composition, particle size, density, confinement and geometry on sensitivity levels as it gives an indication of how close the stimulus is to the failure threshold, thereby obtaining a more reliable insight into an explosive response than that obtained from simple go-no-go tests.

This report describes an instrumentation system that measures the run to detonation distance in an explosive material initiated by a shaped charge jet. Electronic probes are used to measure the transit time over a known length of explosive, which when combined with calculated penetration velocities of the shaped charge jet, allow the run to detonation distance in the explosive to be calculated using an iterative process. A practical application of the system is illustrated with a series of experiments carried out to measure the effect of steel confinement on the run to detonation distance in a Composition B acceptor.

2. System Overview

The run to detonation distance in an explosive material can be calculated from data relating to the position of the onset of detonation from a propagating shock [1]. In the case of initiation by a shaped charge jet, the arrival time of the jet at the explosive surface can be measured and the subsequent penetration of the acceptor explosive by the jet can be calculated using classical jet penetration theory [2]. In this way, a measurement of the transit time across the explosive acceptor can be used to determine the run to detonation distance. The system can also be used when the initiation stimulus is other than a shaped charge jet, provided the appropriate shock propagation equations are specified within the software.

In the run to detonation measurement system, timing pulses from electronic probes in the charge assembly (figure 1) are recorded on a digital oscilloscope and transferred to a laptop computer for analysis. These measured arrival times, along with other experimental data relating to the charge assembly and donor shaped charge properties, are used as the input to the run to detonation calculation program. The run to detonation distance and other data relating to the donor shaped charge penetration can thus be calculated and displayed, usually within seconds of the charge being fired.

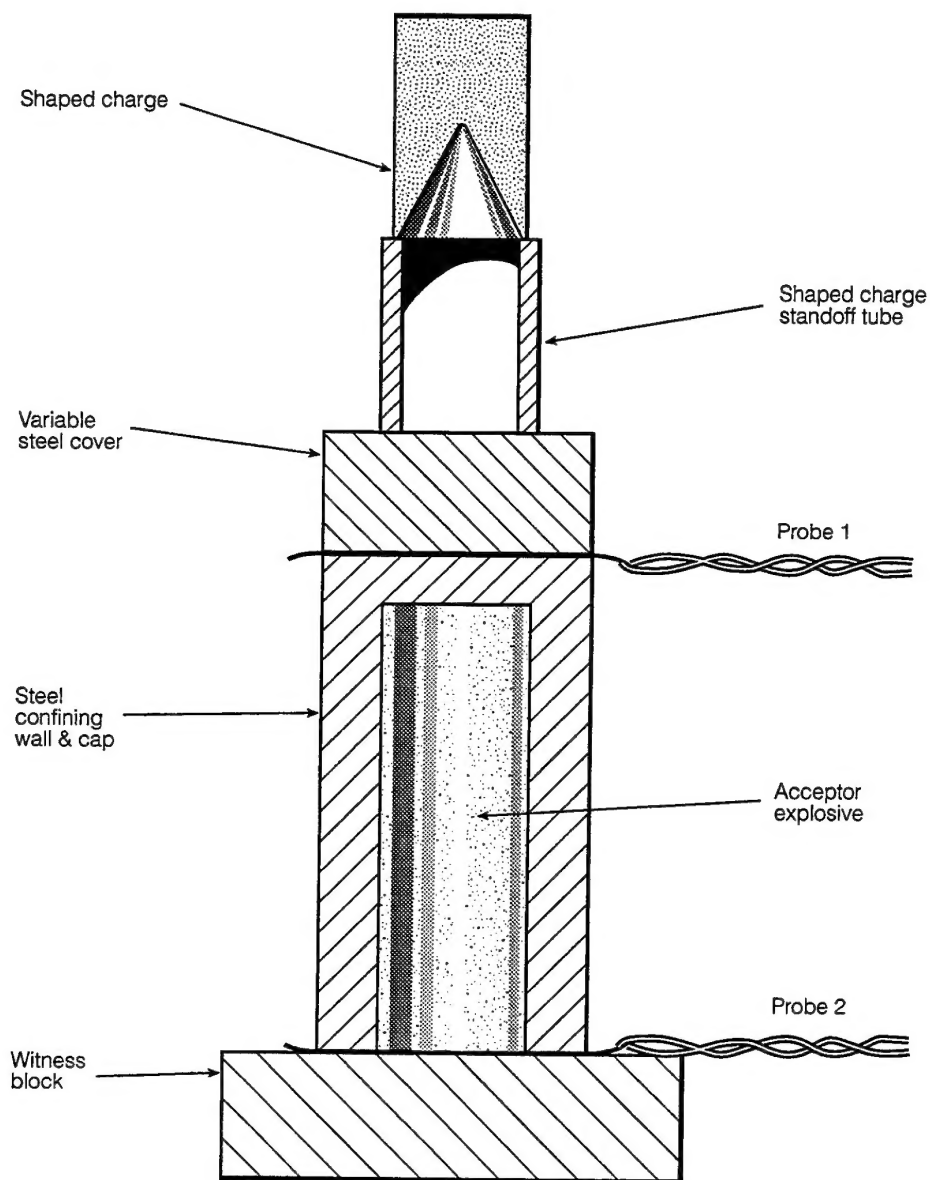


Figure 1: A typical experimental assembly containing probes to measure the run to detonation distance in an explosive material.

A feature of the system is that it is able to be used with both unconfined and confined rounds. This gives the technique advantages over others such as flash x-ray or high speed optical cameras which, because of a confining material, may require significantly more complex setups to avoid damage caused by fragmentation, or which cannot directly record the reactions inside the acceptor.

3. System Operation

3.1 Hardware Elements

The hardware which makes up the instrumentation system consists of three main sections:

- (i) probe event box and power supply,
- (ii) digital oscilloscope, and
- (iii) laptop computer with GPIB interface to the oscilloscope.

A schematic representation of the hardware components is shown in figure 2.

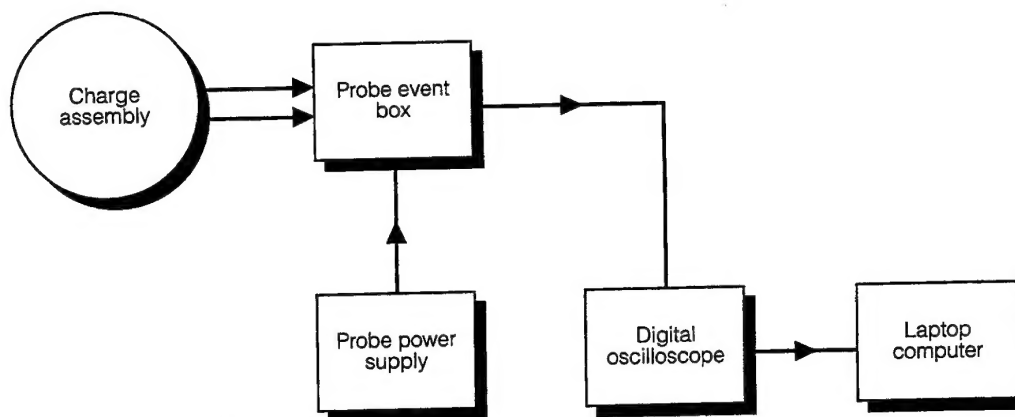


Figure 2: Schematic diagram of the AMRL run to detonation instrumentation system.

3.1.1 Probe event box and power supply

The transit time through an explosive sample is measured with electrical probes placed at known positions in the charge assembly. These probes are connected to a probe event box, which is energised by a DC power supply providing a current limited output voltage, selectable between ± 20 to ± 300 VDC. The higher voltage outputs are used in electrically noisy environments to enable voltage threshold levels to be set

high. The probe event box converts signals from the probes included in the charge assembly to an electrical signal suitable for recording by a digital oscilloscope.

A range of different probes can be used, from make or break type probes to piezoelectric pins, depending on the specific configuration of the event box and the type of probes best suited to the charge assembly. Generally however, a simple laminated type of make screen is used to record the time of arrival of the jet, and an interlaced copper grid is used to record the time of arrival of the detonation front. These two types of probes are shown in figure 3.

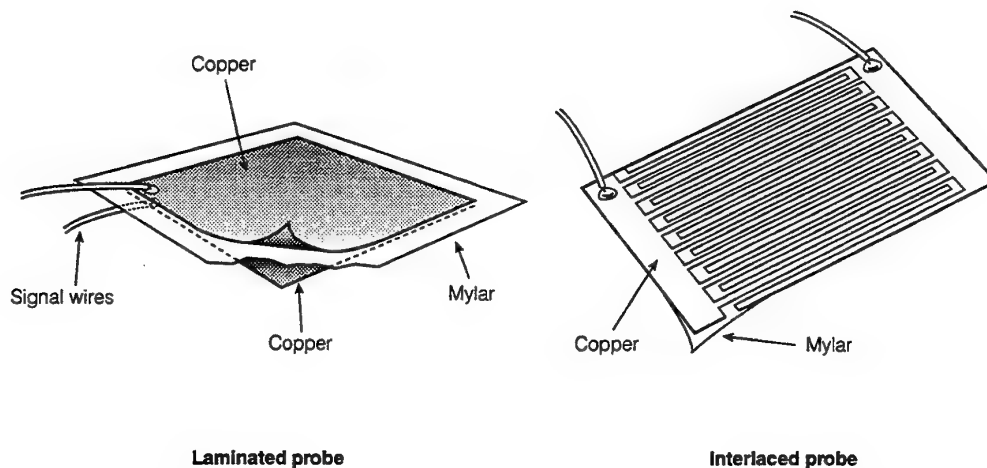


Figure 3: Two types of probe used to record the time of arrival of (a) the shaped charge jet, and (b) the ionised detonation front.

The laminated make probe is designed to function when a metallic projectile completes the electrical circuit by puncturing the central insulating layer of the probe, thereby shorting the top and bottom layers of copper. The interlaced probe is designed to function when an ionised front, the detonation wave, completes the electrical circuit by shorting adjacent conductors of the probe as the detonation wave strikes the probe surface.

Twin core shielded microphone cable is used to connect each probe to the event box, and several individual pulses or a single multiplexed train of pulses can be generated depending on the type of event box in use. The event box is usually located near the charge assembly (approximately 10 metres away) and the pulses are transmitted to a remote recording station over coaxial cable. The circuit for a typical make probe event box (the most common used for these experiments) is shown in figure 4. Other types of event boxes and probes are discussed elsewhere [3,4].

A typical output pulse from the probe event box is shown in figure 5. The pulse is generated by a capacitor discharge and has a time constant of approximately 100 μ s. This is a relatively long pulse, but the leading edge is very sharp with a rise time of less than 100 ns. This sharp leading edge makes the pulse ideal as a time of arrival

indicator, and the long duration of the pulse allows it to be recorded even with relatively slow digitising rates (less than 100 MS/s). Slow digitising rates may be necessary if a long recorded time interval (recording window) is necessary and the digitising instrument is not capable of storing a sufficiently large number of digitised points.

Pulses of shorter duration are required if the output of the event box is to be multiplexed and event boxes producing pulses with a 30 ns time constant and multiplexed output can be used with the system. A similar event box is used to produce multiplexed pulses in velocity of detonation measurements, where the recording window is usually short and a fast sampling rate is used [3].

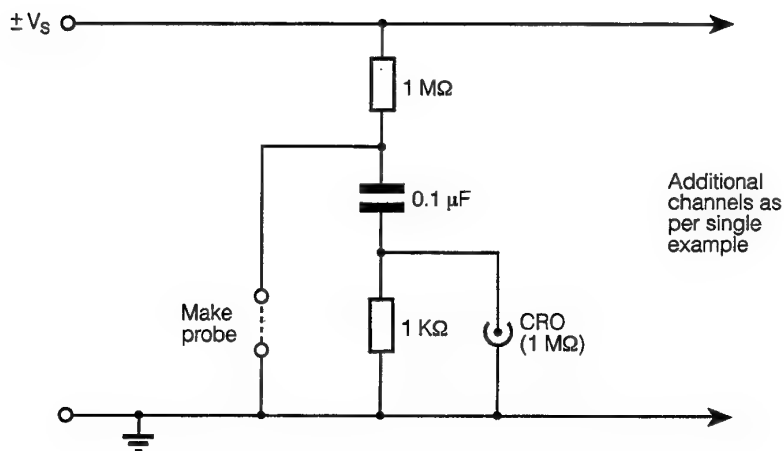


Figure 4: Circuit diagram for a make probe event box.

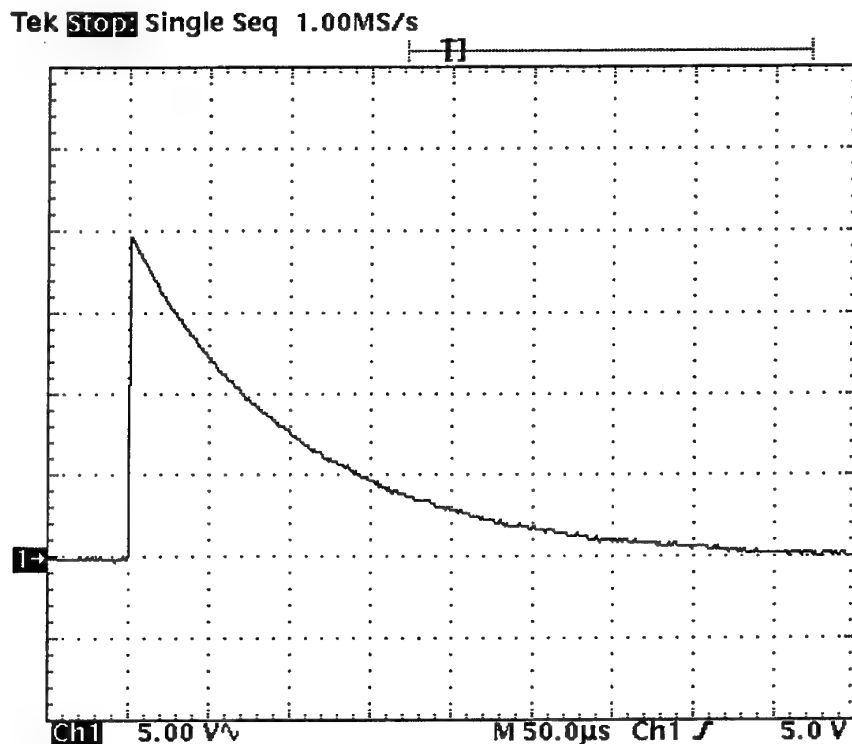


Figure 5: Typical time of arrival pulse output from the probe event box.

3.1.2 Recording instrumentation

In our system, the recorder used for capturing the event pulses is a Tektronix model TDS540 digitising oscilloscope. It is a 4 channel instrument with 500 MHz analogue bandwidth, 50 k sample points memory per channel and sampling rates up to 1 GHz. It allows very fast events to be captured with long recording windows and is easily interfaced to a laptop computer over a GPIB connection. Generally, any similar recorder can be used that satisfies the sampling rate and record length requirements if it can be connected to a GPIB or other data interface.

Once the event pulses have been captured on the oscilloscope they are transferred to a Toshiba T6400 DXC laptop computer for analysis and storage. This Computer was chosen because it is fully portable, is relatively fast, was able to be configured with a GPIB card and provided a colour screen for easy identification of multi-channel records. Any machine capable of interfacing over a data link would be suitable once the software was modified for the machine specific requirements.

With this system, all necessary acquisition and processing can be carried out at the test location and the results used to guide further experiments on site.

The system has been designed to allow various equipment to be used which is consistent with the following minimum criteria:

- Digitising Oscilloscope with GPIB interface,
- IBM AT or compatible Personal Computer with PC or MS DOS 3.0,
- IBM colour VGA graphics card or any other compatible card,
- IBM or compatible 640 x 480 pixel colour VGA monitor,
- At least 1 megabyte of Random Access Memory,
- Hard disk with at least 1 megabyte available,
- Microsoft mouse or any other compatible pointing device,
- HP-IB interface card and cable,
- HP LaserJet II printer or higher or compatible printer with built-in HPGL command or HP 7550A Plotter or compatible plotter with built-in HPGL command.

3.2 Software Elements

The software system can be divided into 3 separate sections:

- (i) event pulse acquisition,
- (ii) waveform analysis to determine pulse arrival times, and
- (iii) calculation of the run to detonation distance.

A flow diagram which indicates the flow of information is shown in figure 6.

3.2.1 General development details

The acquisition and run-to-detonation program was developed using Borland C++ version 3.0 software development tools under a DOS environment. A 486 desktop computer system with eight megabytes of Random Access Memory (RAM) and a 640 x 480 pixel super VGA colour monitor was used during the development phase, but the software is quite flexible in terms of computer hardware requirements. It will run on a 286 computer system with one megabyte of RAM, only at a slower pace. It does however require a 640 x 480 pixel VGA color monitor, or problems such as color scheme mismatching or missing parts of the screen layout will occur.

The acquisition software consists of one executable file (tds540.exe). The run to detonation calculation software consists of an executable file (rtd.exe), a barrier material data file (matprop.fil) and a shaped charge jet data file (jettip.fil). The two data files in the run to detonation calculation software provide access to a data base of material and shaped charge data and can be called up by the user during the data entry stage of the program. The run to detonation calculation program will operate without the two data files, however, the information contained in them will not be accessible from within the program.

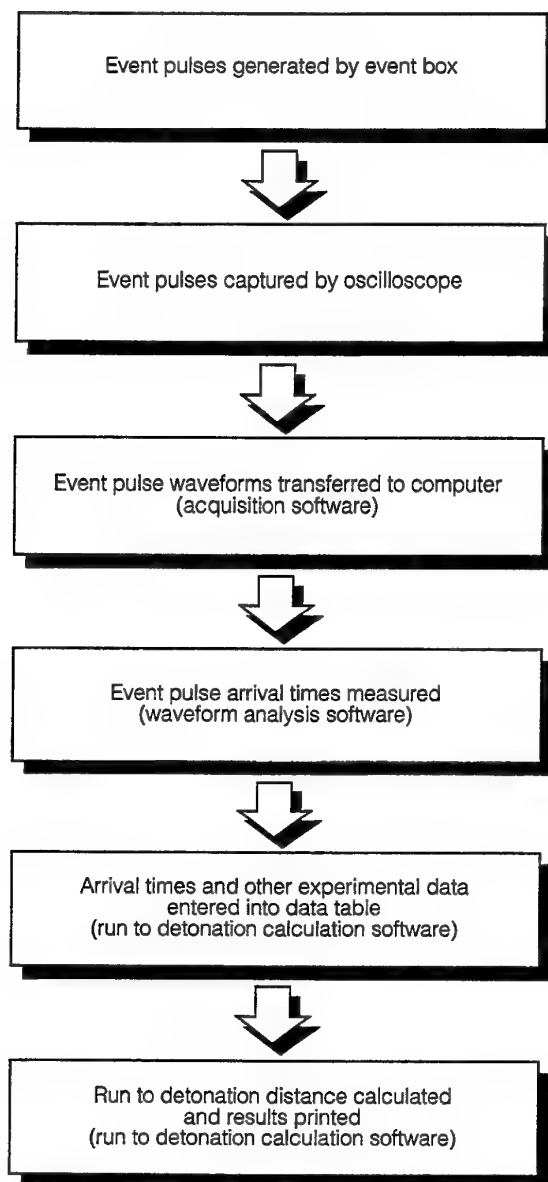


Figure 6: Schematic representation of the data flow in the run to detonation system.

3.2.2 Acquisition software

The acquisition software was developed to acquire a recorded waveform and carry out the analysis to measure the arrival time of each event pulse. The acquired waveform is displayed on the computer screen and sections of it can be magnified to simplify the analysis process. The program is capable of carrying out the necessary waveform analysis automatically, or the user can invoke various options which allow a manual analysis to be carried out in the event of non standard waveforms being recorded.

Output from the acquisition software is not currently interfaced directly to the run to detonation calculation program due to memory restrictions of the operating system. Measured times of arrival are manually input to the run to detonation calculation program, which although slightly more time consuming, does not present any problems. A full description of the acquisition program and operating instructions is contained in appendix A.

3.2.3 Run to detonation calculation software

The run to detonation calculation program is a graphics oriented, user friendly program that produces a graphical display of the calculated run to detonation results. The user has access to a range of intermediate calculation values as well as the final result and an additional analysis feature which traces the path of the shaped charge jet through the charge assembly.

A method of calculating the initiation of solid explosives by shock waves [1] was adapted for the case of initiation by a shaped charge jet [5]. The run to detonation distance in the explosive acceptor is calculated from the measured transit time and the jet penetration velocity which is calculated with equations describing the penetration characteristics of the jet [2,6].

Shaped charge equations

Calculation of the velocity of the leading jet particle (J_L)

The jet equation used in the code is defined in equation 2 which is a modified version of the standard jet equation shown in equation 1. The standard jet equation was modified to account for the situation where a shaped charge is known to produce a jet with a leading constant velocity particle and is taken from the treatment in reference 6.

The difference between the two equations is the additional parameter p added to the denominator of the jet equation. This p value represents the barrier thickness that is required to erode the leading constant velocity particle. Note that if p is equal to zero, the equation reduces to the standard jet equation.

$$V_j = V_j' \left[\frac{\tau + s}{s} \right]^{-\gamma} \quad (1)$$

$$V_j = V_j' \left[\frac{\tau + s}{s + p} \right]^{-\gamma} \quad (2)$$

where: V_j is the velocity of the leading particle,
 V_j' is the velocity of the previous leading particle ie. the initial jet velocity or velocity of the leading particle at the bottom of the previous barrier,
 τ is the target thickness,
 s is the distance from the virtual origin [6] of the shaped charge to the surface of the barrier,
 γ is the square root of the ratio of the target material and jet material densities, and
 p is the barrier thickness required to erode the leading constant velocity particle.

Calculation of the density ratio (γ) of the jet and barrier

Gamma (γ) is the parameter that defines the interaction between the jet and the barrier. Its value depends on the density of the jet material and that of the barrier (target) material. It is defined in equation 3.

$$\gamma = \sqrt{\frac{\rho_{target}}{\rho_{jet}}} \quad (3)$$

where: ρ_{target} is the density of the target material.
 ρ_{jet} is the density of the jet material, and

The target may be made up of several different materials and this can be taken into account by using the density ratio for each jet/material combination in turn.

Calculation of the barrier thickness (p) required to erode the leading constant velocity particle

Because of the contribution of the leading constant velocity particle to the penetration of a target, the standard jet equation was modified to include the penetration due to this particle as discussed above. The amount of penetration for a given shaped charge will depend on the density of the target, so for different cover materials, the depth of penetration by this particle is calculated using equation 4.

$$p = \frac{l}{\gamma} \quad (4)$$

where: l is the initial or the remaining length of the leading constant velocity particle entering the target.

Calculation of the remaining length (l) of the leading constant velocity particle after penetration of a barrier

If a barrier thickness is less than the value of p calculated for that barrier, there will be a length of the leading constant velocity particle remaining when the jet enters the next barrier. The remaining length is calculated using equation 5.

$$l = \gamma(p - \tau') \quad (5)$$

where: τ' is the current barrier thickness.

This particle length is substituted into equation 4 which calculates the barrier thickness required to completely erode the remaining part of the leading constant velocity particle (p). This value of p is then substituted into equation 2.

Calculation of the jet penetration velocity (U_p)

As the shaped charge jet penetrates the barrier material, the penetration velocity, which is different to the velocity of the leading particle (in air) given by equation 2, is calculated using equation 6 from classical jet penetration theory [2].

$$U_p = \frac{V_j}{1 + \gamma} \quad (6)$$

where: U_p is the velocity of the leading particle (in air).

This penetration velocity is used to calculate the transit time through the charge assembly.

Calculation of the barrier transit time (B_t)

The jet penetration velocity is not constant as it penetrates a barrier. From equation 2, the leading particle velocity and therefore the jet penetration velocity decreases with distance into the target. Over short distances the decrease is approximately linear and the barrier transit time can therefore be approximated by equation 7.

$$B_t = \frac{\tau'}{\overline{U}_p} \quad (7)$$

where: B_t is the barrier transit time, and

$$\overline{U}_p = \frac{U_p(\text{top}) + U_p(\text{bottom})}{2} \text{ is the average penetration velocity between the top and bottom of the barrier.}$$

Calculation of the reaction transit time through the explosive acceptor (t_{exp})

The transit time through the acceptor is calculated as the time difference between the first event pulse (t_1) and the last event pulse (t_2). However, as the program has been designed for use with confined acceptor rounds which are fabricated with an irremovable cover, the first probe is not in contact with the surface of the explosive. The transit time through the acceptor is therefore given by equation 8.

$$t_{exp} = t_2 - t_1 - t_b \quad (8)$$

where: t_1 is the first event pulse,

t_2 is the last event pulse, and

t_b is the transit time through the barrier on top of the acceptor.

In a charge assembly that does not consist of an acceptor with an irremovable cover, the thickness of the probe must be included as the final barrier. In all other firings, the probe thickness can be neglected.

Calculation of the lost time in the explosive acceptor (t_{lost})

The lost time is calculated as the time difference between the measured transit time through the acceptor and the transit time through the acceptor that would have been measured for steady state detonation through the acceptor.

$$t_{lost} = t_{exp} - \frac{L}{VoD} \quad (9)$$

where: L is the length of the acceptor, and

VoD is the detonation velocity of the acceptor material.

Calculation of the run to detonation distance

The run to detonation distance in the explosive acceptor is taken from the treatment given in reference 5 and is calculated using an iterative process in which a first approximation of the run distance is calculated using the initial jet penetration velocity in the acceptor. Because of the nature of the penetration process, the initial penetration velocity in the acceptor will be faster than the average penetration velocity between the top of the acceptor and the point at which the transition to detonation occurs. This initial run distance is then used to calculate an average penetration velocity between the surface of the acceptor and the transition point, which in turn, is used to calculate a new run distance. This process is continued for 4 cycles after the initial calculation (which is usually enough for convergence of the run distance to within 0.1 mm). The result of each iteration is presented in tabular form in the results output so the user is able to identify any irregularities.

The equations used in the iteration process are given in equations 10-13.

Calculation of the run to detonation distance (rtd)

$$rtd = \frac{L - VoD * t_{exp}}{1 - \frac{VoD}{\overline{U}_p(exp)}} \quad (10)$$

where: $\overline{U}_p(exp)$ is the mean penetration velocity in the acceptor (equation 12).

Calculation of the mean jet velocity in the acceptor charge ($\overline{V}_j(exp)$)

$$\overline{V}_j(exp) = \frac{V_j(top) + V_j(rtd)}{2} \quad (11)$$

where: $V_j(top)$ is the jet velocity on the top of the acceptor, and
 $V_j(rtd)$ is the current iteration jet tip velocity derived from equation 2.

Calculation of the mean penetration velocity in the acceptor charge ($\overline{U_p^{(exp)}}$)

$$\overline{U_p^{(exp)}} = \frac{U_p^{(top)} + U_p^{(rtd)}}{2} \quad (12)$$

where: $U_p^{(top)}$ is the penetration velocity on the top of the acceptor, and
 $U_p^{(rtd)}$ is the current iteration penetration velocity.

Both of these values are derived from equation 6.

Calculation of the run to detonation time (t_{rtd})

This is simply the run to detonation distance divided by the average penetration velocity, as defined in equation 13.

$$t_{rtd} = \frac{rtd}{\overline{U_p^{(exp)}}} \quad (13)$$

Computational procedures

The process by which the program calculates the run to detonation distance is shown in the flowchart of figure 7.

4. Run to Detonation Measurements

4.1 Use of the Run to Detonation Program

The run to detonation distance calculation program displays the screen shown in figure 8 when it is started.

Striking any key will display the main menu screen with the options shown in table 1. The required function is selected by pressing the appropriate function key.

Note. At different stages throughout the program, the function keys are redefined to carry out different functions.

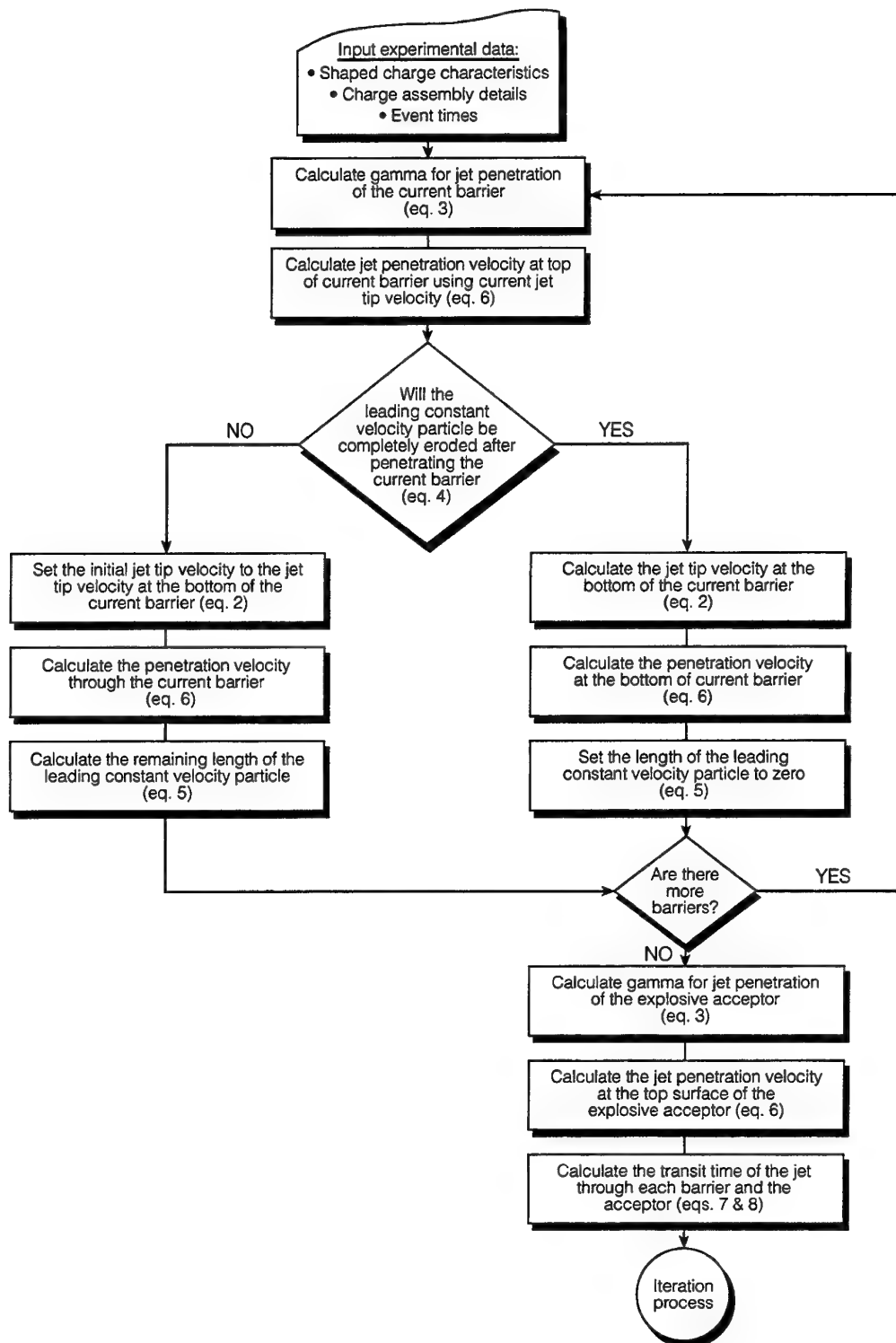


Figure 7: Flowchart describing the basic operation of the run to detonation calculation program.

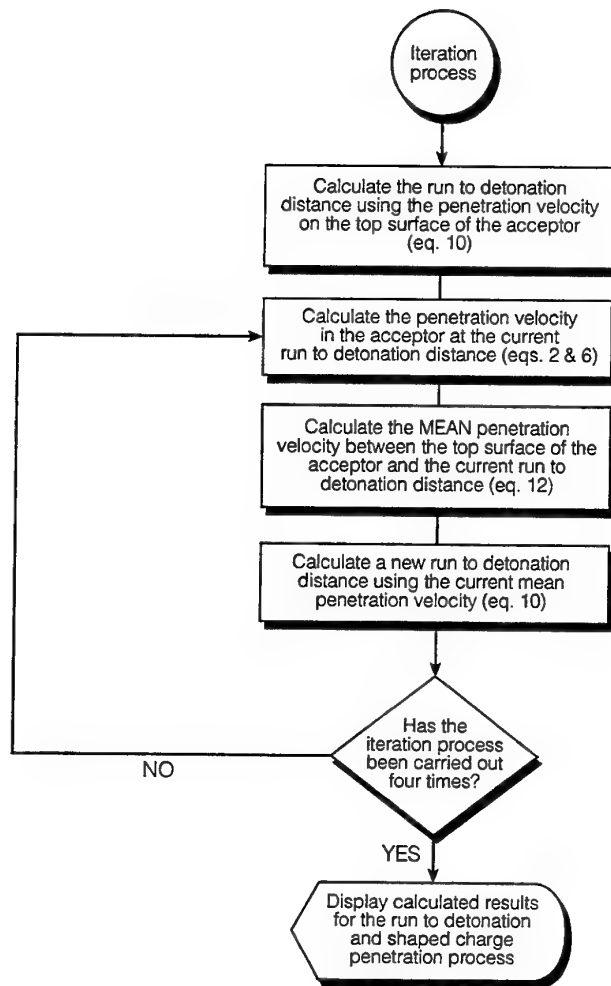


Figure 7 (Contd): Flowchart describing the basic operation of the run to detonation calculation program.

Notes:

1. If the leading constant velocity particle is not completely consumed before entering the acceptor explosive, a violation flag is set and a warning message is displayed. In this case, the iteration process ignores the remaining jet tip length and treats the shaped charge jet as a standard jet described by equation 1. The calculated run to detonation distance will, in these circumstances, be in error by a small positive amount. However, situations like this will rarely occur, and are identified with the warning message on the screen.
2. If the calculated run distance is within ± 20 mm of the end of the acceptor, a warning message will be displayed to indicate that the predicted result (detonation or non-detonation) may be incorrect due to inaccuracies in the calculation as discussed in section 5.0, or that the length of the acceptor charge may not be long enough for this particular experiment. For example, if the acceptor charge was not long enough for the reaction to build up to a detonation, the observed result would be a non-detonation. A longer acceptor charge may, in fact, run up to a detonation. The warning message advises the user that the experiment may need to be repeated with a longer acceptor charge.
3. The run to detonation calculation may calculate a run distance longer than the length of the acceptor charge. In this case the result will be displayed as a non-detonation but the user can identify that a longer acceptor charge may be required by the run distance warning.

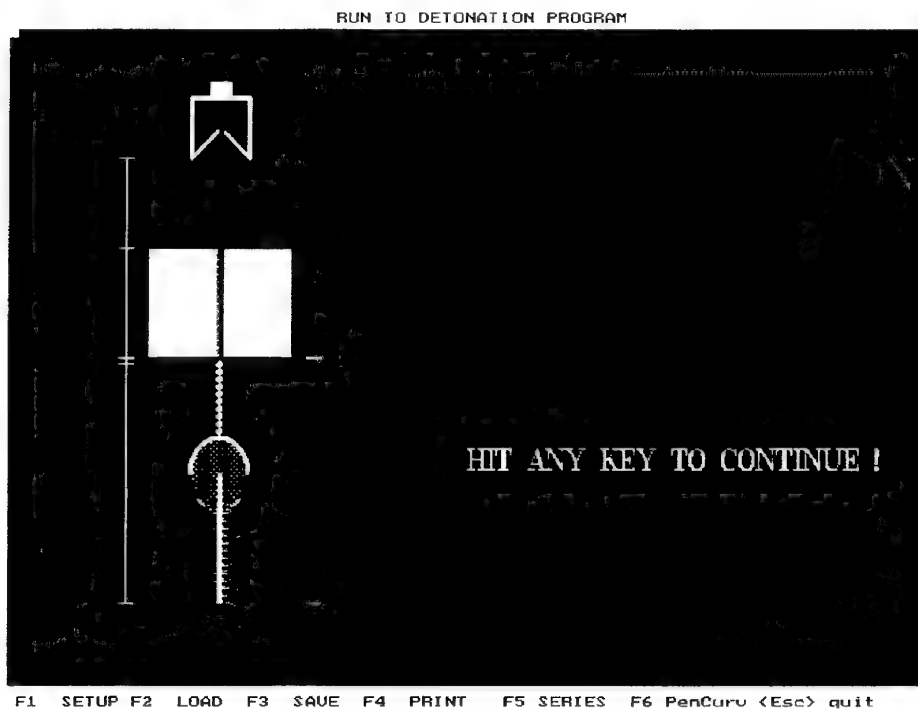


Figure 8: Start-up display for the run to detonation program.

Table 1: Functions available from the main menu display in the run to detonation distance calculation program.

| Button | Function |
|--------------|---|
| F1: Setup | Displays the data table ready for entry of new data. The previous values used are presented as the existing entries in the data table and new data is overwritten where required. |
| F2: Load | Loads a previously saved data file into the data table. |
| F3: Save | Saves the current data table to a file. |
| F4: Print | Sends the current data and results to the output device. |
| F5: Series | Allows data base information to be assigned to the file. |
| F6: Pencurve | Displays an interactive plot of the path of the shaped charge jet through the charge assembly. From this display, velocities and position-time data for the calculated result is available to the user. |
| (esc): Quit | Exits the run to detonation calculation program. |

Choosing option F1 from the main menu functions begins the data entry stage of the program by displaying a table with data entry boxes. Measured event times are input to the run to detonation program along with other experimental data by typing the information in the boxes on the right hand side of the screen. Material and shaped charge data for a range of materials and shaped charge designs is available by calling up the appropriate menu with the function keys F2 and F3 during this stage of the program. Up to five different barrier materials can be selected to be included in the charge assembly.

The arrival times of the event pulses are entered in the initial time and final time boxes. These two times must correspond to event pulse arrival times on the top and bottom of the acceptor respectively. As previously stated, the program has been written for acceptors cast into a capped confining cylinder. The difference between the initial and final event times is therefore the transit time through the cap material and the acceptor charge. In an experiment without this cap material, the probe must be treated as a barrier, and its thickness and density must be entered as the last barrier. Typical values for the laminated type of probe generally used in this position are 0.07 mm thick with a density of 8.93 g/cm^3 . Treating the probe as a barrier in this way will have a negligible effect on the calculated run distance. However, if the probe is not included as a barrier in this situation, the program will assume the initial event pulse occurred on top of the last barrier and the result will be incorrect. The bottom probe must, however, always be in contact with the bottom of the explosive charge.

When the data has been correctly entered, the run to detonation calculations are performed by pressing F1. The screen displays a graphical representation of the run calculation on a distance-time plot of the jet and detonation front path through the acceptor. A copy of the output from a calculation is shown in figure 9.

Jet penetration velocities and transit times through each barrier are displayed in the bottom table under the distance time plot as an aid to quality assessment of the result, and function keys F1 and F2 are used to call up tabulated data relating to the iterative calculation values or calculated data relating to the penetration of the shaped charge jet through the charge assembly. The esc key returns the program to the setup menu, from which, alterations can be made to incorrect data, or the user can return to the main menu by hitting the esc key again.

A further option is provided to track the path of the shaped charge jet through the experimental set-up. This option can be called up with function key F6 from the main menu. The jet tip velocity and penetration velocity are displayed graphically and movement of the cursor with the arrow keys displays those values, together with the time from the top of the first barrier in the experimental set-up. This interactive display is also useful as an aid to selecting the recording window on the oscilloscope and is shown in figure 10 for the charge assembly of figure 1.

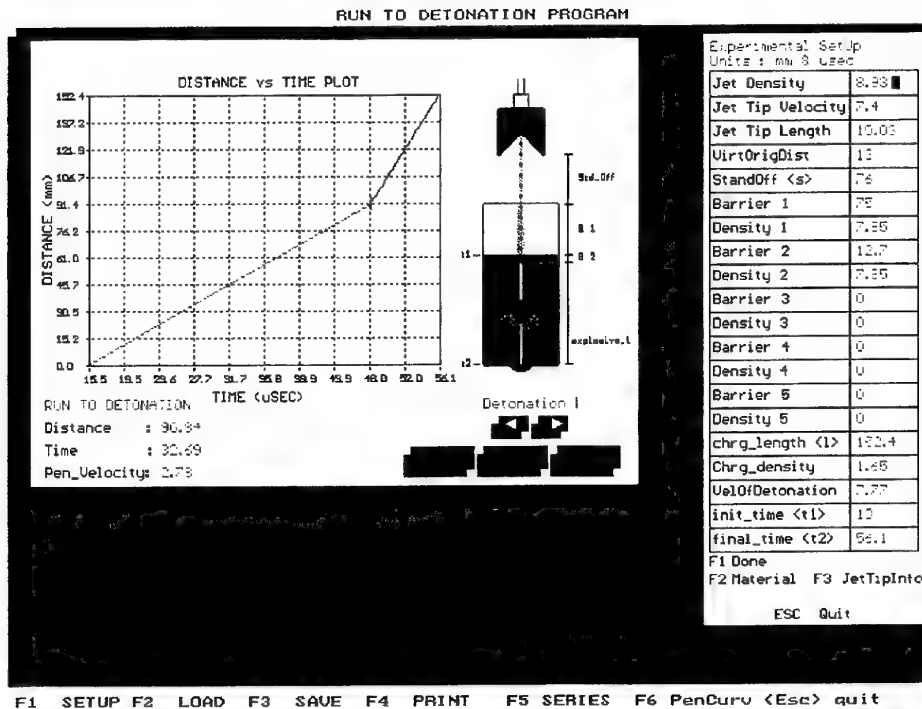


Figure 9: Output data from the run to detonation calculation for the charge assembly of Figure 1.

The calculated run to detonation distance is also displayed on this plot (shown as a cross within a circle). This point does not lie on the actual curve as the curve is plotted from equation 2 and represents the theoretical instantaneous velocity at points along the jet and in the targets. The indicated run to detonation point represents the measured run distance and the average velocity between the top of the explosive and calculated run to detonation point, which will always be greater than the instantaneous velocity at that point.

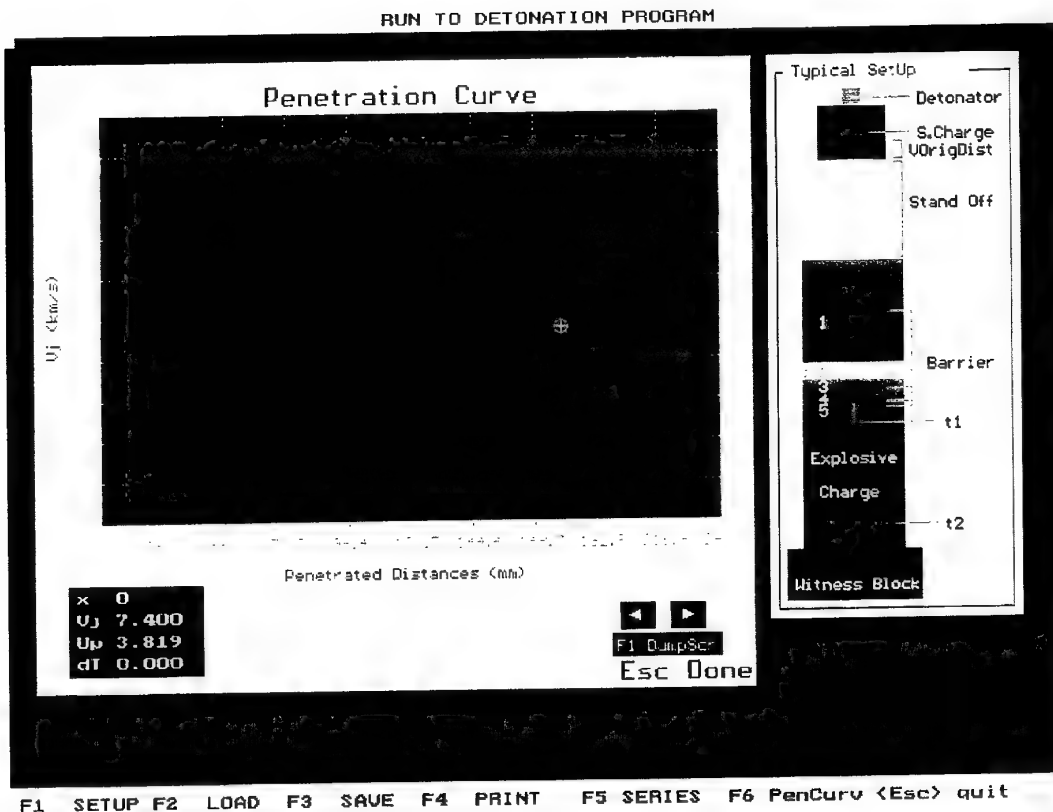


Figure 10: Velocity-distance plot for a shaped charge jet penetrating the charge assembly shown in Figure 1.

5. Results and Discussion

Figure 11 shows the result from an experiment in which flash x-ray was used in conjunction with probes to measure the run distance in a 30 mm mild steel covered, unconfined Composition B acceptor. Because an unconfined acceptor was used, flash x-ray was able to record the detonation transition. With a confined acceptor, the case material obscures the image and produces fragments which may destroy the recording films. Note the position of the first event probe on top of the acceptor. Because the acceptor is unconfined, the confining cap is not part of the acceptor charge casting, so the first probe can be placed directly on the top surface of the acceptor. The probe must therefore be included as the final barrier material in the run to detonation calculation program data table.

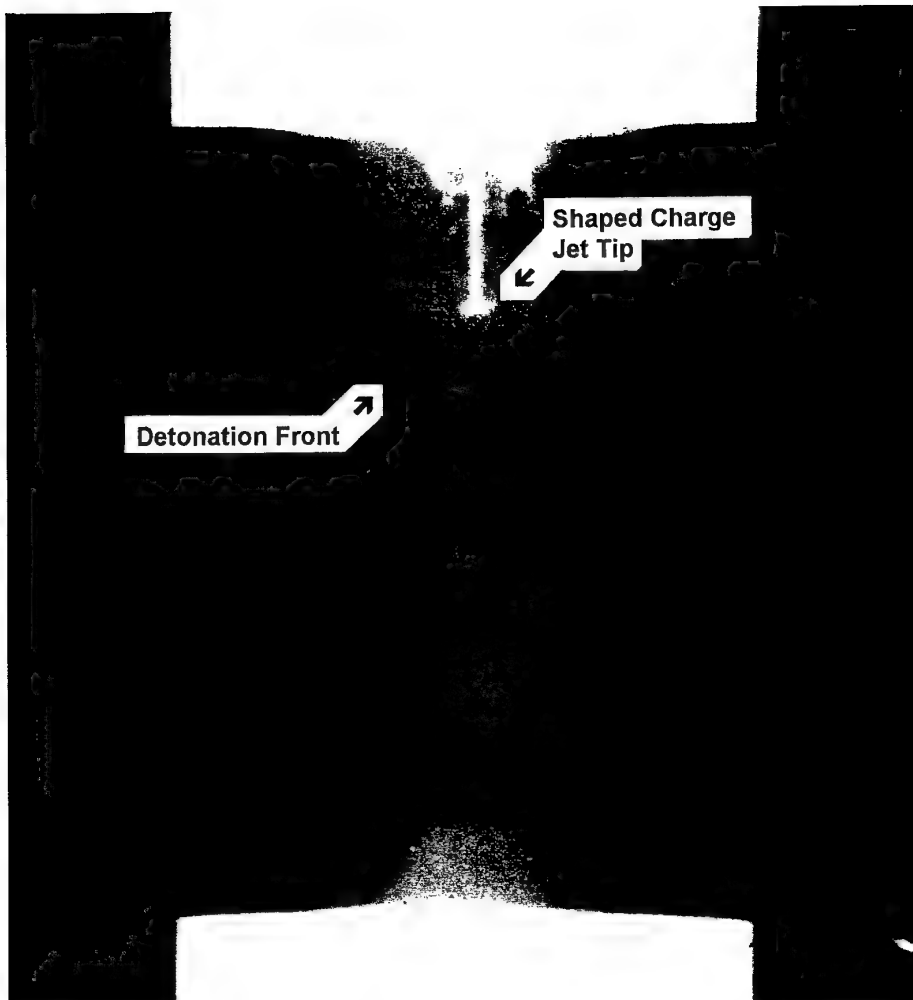


Figure 11: Flash x-ray of a run to detonation probed shot.

The flash x-ray picture clearly shows the early stages of the expansion of the detonation front in the acceptor. The transition point can be estimated from the flash x-ray picture by extrapolating the observed detonation front back to an origin behind the imaged front. The position of this origin relative to the other features visible in the flash x-ray picture will depend on the time elapsed between when the picture was taken, and when the transition actually occurred. The run distance in this experiment was estimated from the flash x-ray as approximately 22 mm. From the probe data, the calculated run distance was 25 mm, which is in good agreement with the flash x-ray estimate.

Variation in the measured run distance for a given charge assembly can be due to several factors:

- (1) The transition to a detonation actually occurs at a point several millimetres in front of the penetrating jet tip, in the jet bow wave [7]. The first event probe measures the arrival of the jet tip, not the bow wave in front of the jet.
- (2) The jet penetration velocity used in the calculation of the run distance will be different from the actual penetration velocity because of slight round to round variation in the shaped charge producing variation in the jet parameters, eg. tip size and velocity.
- (3) The calculations assume an instantaneous change from the penetration velocity of the shaped charge jet to the detonation velocity of the acceptor charge. There will in fact be a transition period in which the bow wave accelerates up to the full detonation wave velocity.
- (4) In experiments carried out with cover thicknesses close to the critical cover thickness, significant variation in the run distance is observed. This is considered to be a real effect as a result of the reaction front becoming unstable under this condition where the initiation is marginal [5], and is a result of round to round variation in the explosive acceptor.
- (5) For thin covers, initiation of the explosive can result from a rapidly decaying impact shock which is transmitted into the acceptor when the jet strikes the cover. This mechanism can produce very short runs and the current treatment cannot be strictly applied since it is not the penetrating jet in the explosive that is responsible for detonation. A very short run to detonation measurement (or a negative value which indicates that the acceptor detonated before the jet entered it) is indicative of the process, however accurate values are not achievable without modification of the analysis software.

Table 2 shows some typical results from a series of tests to determine the run to detonation distance in a mild steel covered, unconfined and confined Composition B acceptor. The experimental assembly was as shown in figure 1, with the steel cover thickness being varied to vary the velocity of the shaped charge jet entering the acceptor. The diameter of the acceptor was 38 mm with a confining wall thickness of 19 mm.

Table 2: Run to detonation data for unconfined and confined Composition B.

| Unconfined Composition B | | | | Confined Composition B | | | |
|-------------------------------|---------------------|---------------------|----------------------|-------------------------------|---------------------|---------------------|----------------------|
| Jet Velocity (mm/ μ s) | t_1 (μ s) | t_2 (μ s) | Run Distance (mm) | Jet Velocity (mm/ μ s) | t_1 (μ s) | t_2 (μ s) | Run Distance (mm) |
| 5.2 | 47.4 | 66.4 | 39 | 4.3 | 10.0 | 65.4 | 126 |
| 5.2 | 48.8 | 68.2 | 41 | 4.3 | 0.0 | 46.1 | 90 |
| 5.4 | 0.0 | 17.8 | 32 | 4.3 | 0.0 | 46.0 | 91 |
| 5.6 | 0.0 | 17.2 | 30 | 4.7 | 5.8 | 40.4 | 51 |
| 5.8 | 41.6 | 58.0 | 28 | 4.7 | 0.0 | 34.0 | 49 |
| 6.3 | 0.0 | 15.7 | 25 | 5.5 | 40.6 | 64.5 | 46 |
| 7.1 | 33.9 | 41.3 | 11 | 6.0 | 37.8 | 57.2 | 29 |
| 7.3 | 32.9 | 40.1 | 9 | 6.0 | 37.2 | 63.4 | 32 |
| 7.4 | 32.7 | 39.4 | 2 | 6.4 | 33.3 | 53.4 | 33 |
| 7.4 | 30.4 | 42.8 | 2 | 6.5 | 33.8 | 51.8 | 23 |

Note that several of the t_1 values in table 2 are zero. This is a result of using the event probe pulse to trigger the recording instrument which is sometimes necessary. In this case it is necessary to add a constant value to the measured times (which does not change the value of $t_2 - t_1$) because the run to detonation program does not accept a zero time.

The calculated results shown in table 2 are estimated to be accurate to within a few millimetres of the actual run distances, and are quite reproducible for cover thicknesses away from the critical cover thickness.

Measurement of the run distances in these experiments has allowed a quantitative assessment to be made of the effect of confinement on the run distance in the Composition B acceptor. Figure 12 presents the results shown in table 2 as a plot of the jet velocity entering the acceptor charge verses the measured run to detonation distance.

The zero run distance is attributed to initiation of the acceptor by the impact shock transmitted through the thin cover. As the cover thickness increases, the velocity of the jet tip entering the acceptor (and therefore the penetration velocity) is reduced, and run distances greater than zero are measured for the transition to detonation from the bow wave shock associated with the jet penetration of the acceptor [8]. Lower penetration velocities of the jet require longer run distances over which the bow wave shock can build to a transition to detonation.

Deviation of some data points from the fitted curve is indicative of the variability which is inherent in these measurements. Small variations in the actual velocity of the shaped charge jet compared with the theoretical value can introduce errors into the calculated run to detonation distance. Several shots are often fired at one level to minimise this effect. It is also common to observe a large variation of run distances near the critical condition where the explosive reaction is somewhat unstable.

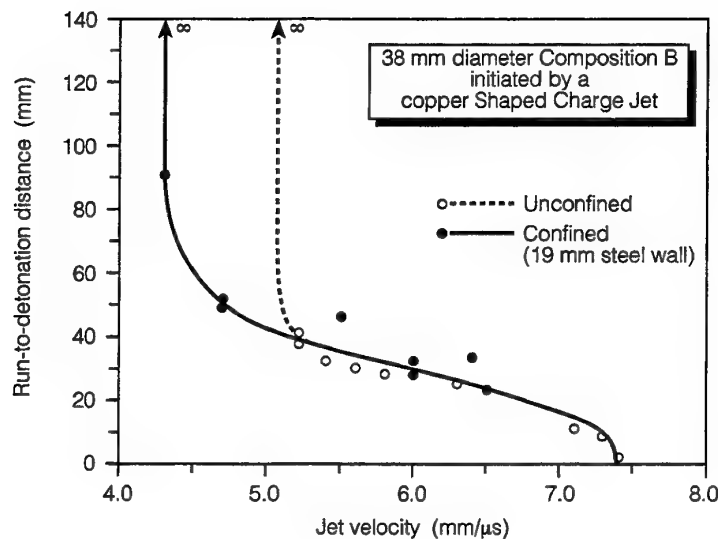


Figure 12: Run to detonation distance versus jet penetration velocity for mild steel covered Composition B.

Examination of figure 12 shows two significant features. Firstly, the run distance extends to an infinite distance (no transition to detonation occurs) consistent with the failure of the acceptor charge at jet penetration velocities below the critical value for the initiation of the acceptor. For unconfined Composition B, this critical velocity is approximately 5.2 mm/μs, while for confined Composition B, the critical velocity is approximately 4.4 mm/μs. Secondly, the run distance is independent of the confinement for jet velocities up to about the critical velocity for unconfined charges, and is simply related to the jet penetration velocity and hence the bow wave shock associated with this penetration. A detailed description of these results, which form part of a larger study of confinement effects, is given in reference 5.

The value of this instrumentation method applied to these types of experiments is demonstrated by our measurements, which were made in the field, with minimal instrumentation requirements, simple charge assemblies and very fast turn-around

times between shots (approximately 15 mins). In addition, the run to detonation distances were calculated within about 60 seconds of the shot being fired and each result used to guide further experiments.

6. Conclusions

An instrumentation system has been developed to carry out run to detonation measurements on confined and unconfined explosive acceptors initiated by a shaped charge jet. Experiments using the system in a range of situations have shown it to be reliable in operation and capable of producing on the spot results which are accurate to within a few millimetres.

The hardware can be assembled in a very short period of time, is flexible in its application to different charge assemblies and probing techniques, and is portable. The software is capable of producing a variety of hardcopy output formats, and its design concept makes it adaptable to a variety of experimental configurations for run to detonation studies with or without shaped charge jets.

Current applications involve initiation by shaped charge jets, but experiments in which the initiation stimulus is other than that are possible with this system. This will require the inclusion of the appropriate set of equations describing the initiation source within the analysis software.

7. Acknowledgements

We wish to record our thanks to Michael Chick who manages this work and to Darren McQueen and Lyn McVay for assistance with the experiments.

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Appendix A:

Description of the Acquisition Software

A1: General

The acquisition software acquires the data captured by the oscilloscope and transfers it to the computer where it can be analysed and saved to disk. It requires the single executable file tds540.exe to run, and as there is no need for other supporting files, is easily installed onto an existing system. The only other installation required is the configuration of the select code and address settings which is done once the program has been started. At the end of each session, a file named tds.540 is created to store the current address and select code settings, thereby eliminating the need to configure them every time the software is loaded. When the software is run for the first time on a particular system, the tds.540 file will not exist and the program will use the default select code and address settings (7 and 20 respectively) unless they are changed using the address function key (appendix A2) to match the value set for the device. If the settings are not correct, the program will prompt the user to correct the fault by displaying an error message.

Before acquiring a waveform, the program will automatically detect the number of channels in use, record length and other oscilloscope settings. Once a waveform has been acquired, the program will automatically determine the position of the first pulse in the channel one record, and the last pulse on the last channel in use so that sections of each waveform between these two pulse times can be displayed in a waveform analysis window for detailed analysis (appendix A3). For this reason, it is recommended to connect incoming event channels to successive channel inputs to the TDS540 commencing with the first event pulse into channel 1, the second into channel 2 and so on. This allows the automatic selection of the waveform displayed in the analysis window to include all relevant pulses. It is also necessary to ensure that any channels on the oscilloscope which contain data, are not positioned after any unused channels which have been turned off (ie. channels 1 and 3 contain data, but channel 2 is turned off). If this is not the case a time-out error will terminate the program and any data that has been acquired will not be able to be transferred to the computer. Channels not required may be turned off to reduce the size of the data file and therefore reduce disc storage space.

Immediately after acquisition, the waveforms are automatically displayed on a view-pad. The top window on this pad displays the full waveform of the oscilloscope for each channel. The bottom center window is the waveform analysis window, where a section of the waveform is magnified for a closer examination of the pulses to be used for time of arrival measurements. The section of the waveform displayed in this analysis window is automatically selected as described above or can be manually reselected as described in appendix A3. Manual reselection may be required if spurious pulses are present or if the default threshold level of 10% is not appropriate.

Note: When the acquisition program is initially loaded, it checks to see if it is able to communicate successfully with the oscilloscope. If it can't, an error message will be displayed on the screen as discussed above. In this case the address setting will need to be changed through the software configuration option or by physically changing the settings on the equipment.

A2: Main menu functions

When the acquisition program is first started the main menu screen shown in figure 13 is displayed.

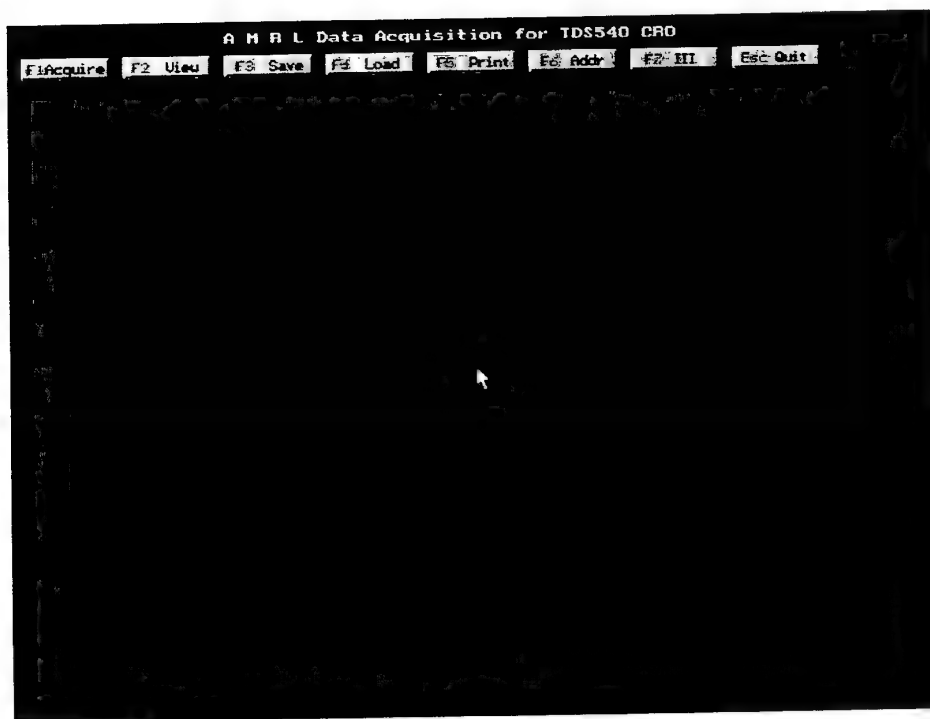


Figure 13: Main menu screen.

This screen provides the user with the options shown in table 3.

Table 3: Main menu functions available at program startup.

| FUNCTION | DESCRIPTION |
|-------------|---|
| F1: Acquire | Acquire the waveform currently displayed on the oscilloscope screen. Having acquired the waveform, the View command is automatically invoked to display the waveform and other analysis features. |
| F2: View | View the waveform currently held in the program memory. In addition to displaying the main waveform, another magnified waveform shows an expanded section, usually between the first and last recorded pulses. Other analysis features are also displayed and are described in appendix A3. It is in this view-pad where the acquired data can be analysed. |
| F3: Save | Save the waveform currently held in the program memory. It is recommended the waveform is saved as soon as possible. |
| F4: Load | Load a previously saved waveform from disk. |
| F5: Print | Print the waveform currently held in the program memory. There are three ways of obtaining a printout: parallel port 1 to a LaserJet Printer, serial port 1 to a plotter, or to disk as a plot file. A printout can also be obtained by using the screen-dump option while the view-pad is displayed (the view-pad will be printed to LPT1 as is, minus the colour scheme). |
| F6: Addr | Configure the select code and address for GPIB communication between the computer and the oscilloscope. This option allows more than one recorder to be connected to the GPIB card. A TEST button enables verification of the settings. Default settings are select code 7 and address 20. |
| F7: III | Displays information about the current software version in use. |
| F8: esc | Exits the program. The user is prompted to save an unsaved waveform before the program ends. |

A3: Waveform analysis functions

After the view option has been called, or immediately after a waveform has been acquired, the display shown in figure 14 will appear on the screen. This is the waveform analysis view-pad and is used for detailed analysis of the acquired waveform. This display consists of two different windows:

Main Waveform Window. This is the top window on the view-pad. The section of waveform displayed in the waveform analysis window can be selected by positioning the mouse pointer in this window, clicking at the start and dragging to the end of the section to be zoomed. The zoom factor will automatically be determined to fill the waveform analysis window with the selected section.

Waveform Analysis Window. This is the bottom center window on the view-pad, where a section of the waveform is magnified for a closer examination of the pulses to be used for time of arrival measurements.

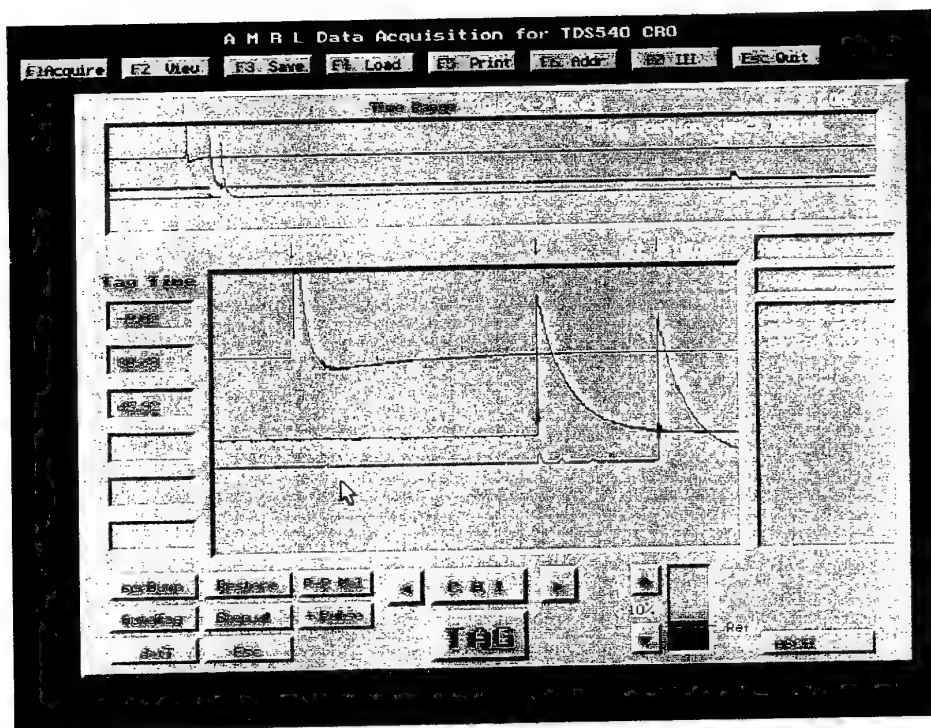


Figure 14: Waveform analysis view-pad.

Note: while the view-pad is displayed the main menu function keys are not active.

The following features (table 4) have been implemented as functions within the view-pad for quick analysis of the acquired waveform.

Table 4: Functions available when the view pad is active.

| FUNCTION | DESCRIPTION |
|-------------|--|
| scrDump | Prints the displayed waveform analysis view-pad directly to a LaserJet printer. The printer must be connected to parallel port 1. |
| AutoTag | <p>Automatically determines the location of each event pulse. The time of arrival of each pulse is displayed on the left side of the view-pad in the Tag Time boxes. The location of each pulse is highlighted by a coloured down arrow on top of the waveform analysis window. A different colour is used for each arrow to distinguish between channels. This feature works in conjunction with the Threshold and \pm pulse settings. Two types of AutoTag have been implemented:</p> <ol style="list-style-type: none"> 1. A single pulse per channel with multiple channel capability. 2. Multiple pulses per channel with single channel capability (Ch 1). A maximum of six pulses can be tagged at one time. |
| defT | After the pulses are tagged, this function will calculate the time difference between each pulse and display them on the right side of the view-pad. |
| Restore | Restore the last zoomed waveform in the waveform analysis window to the previous magnification. |
| Step | Enables the operator to change the cursor speed along the waveforms. The default is 1 sample point increment per step but can be altered by the operator to 5, 20, 50 and 1000 sample points increment per step. |
| \pm Pulse | Determines the way in which pulses are automatically detected. For positive pulse detection, the + sign should be selected, while for negative pulse detection the - sign should be selected. |
| Tag or CH x | Manual tag for each channel. The required channel is selected (CH \blacktriangle or \blacktriangledown), the marker is moved to the desired position on the waveform (\bar{a} or \hat{a}) and the point is tagged (TAG) to record the arrival time of the pulse. |
| Threshold | Determines the voltage level at which automatic pulse detection should take place. The default is set to 10% of the peak value, but the operator can vary the value between 1 to 100% using the up or down arrow (\blacktriangle or \blacktriangledown). |

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| 19. ABSTRACT An instrumentation system for the measurement of run to detonation distances in an explosive acceptor has been developed. The system comprises dedicated hardware elements for data acquisition and user friendly, graphical software for the analysis of the measured data. The system has been designed to allow results to be output in a graphical format with fast turnaround times between firings. This report presents a detailed description of the hardware and software components of the instrumentation system and outlines the standard operating procedures in the application of the system to run to detonation measurements. Results from the measurement of run to detonation distances in steel covered, confined and unconfined Composition B which demonstrate the advantages of this system are presented and discussed. | | | | | |